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HVDC Connected Offshore Wind Power Plants: Review and Outlook of Current Research

Jakob Glasdam, Lorenzo Zeni, Mikkel Gryning, Jesper Hjerrild, Łukasz Kocewiak, Bo Hesselbaek, Karsten Andersen, Troels Sørensen
Wind Power, Electrical Systems
DONG Energy
Fredericia, Denmark
jakgl@dongenergy.dk

Mogens Blanke, Poul E. Sørensen, Anca D. Hansen
Technical University of Denmark
Lyngby, Denmark

Claus L. Bak, Philip C. Kjær
Dept. Energy Technology
Aalborg University
Aalborg, Denmark

Abstract—**This paper presents a state-of-the-art review on grid integration of large offshore wind power plants (OWPPs) using high voltage direct voltage (HVDC) for grid connection. The paper describes in detail selected challenges hereto and presents how DONG Energy Wind Power (DEWP) is addressing these challenges through three coordinated PhD projects in close collaboration with leading academia within the field. The overall goal of these projects is to acquire in-depth knowledge of relevant operating phenomena in the offshore OWPP grid, rich with power electronics devices (PEDs) such as the HVDC and the PED widely used in the wind turbine generators (WTGs). Challenges hereto include PED control system interaction (from a stability point of view), assessment of the quality of vendor supplied control systems and their robustness against e.g. short circuits and load rejection. Furthermore, the outcome of the projects will be developed and validated models of e.g. the HVDC system, methodologies for assessment of control system stability and fault identification in implemented control system.**

Keywords-Wind integration; HVDC; wind power control assessment

I. INTRODUCTION

The fact that future OWPPs are increasing in size and located more remotely from shore poses challenges to the wind power industry [1]. The voltage sourced converter (VSC) based HVDC technology seems to be the obvious solution for transmission of the produced power to shore. The VSC-HVDC technology has therefore become the preferred choice for grid connection of a large number of the planned OWPPs in e.g. the United Kingdom round 3 projects, in Germany and in Denmark [2-4].

The VSC-HVDC system is associated with a high initial cost, but the marginal cost per MW is relatively low, making it advantageous to connect multiple OWPPs (or clusters) to a common offshore HVDC hub [1]. Figure 1 shows three candidate configurations for grid connection of OWPPs using HVDC. Whereas BorWin1 in Germany is the only operating HVDC connected OWPP using the point-to-point (P2P) in Figure 1a, it is expected that future grid connections will be made by connecting the offshore HVDC terminal either on the AC and/or on the DC side of the converter (Figure 1a and b). As large OWPP clusters are distributed over a large physical area with different wind conditions it is possible to optimise the utilisation and loading of the HVDC converters using these configurations. As an example, HVDC 1 can be used to transmit the produced power in case of low wind at OWPP 1 and full production from OWPP 2 in Figure 1b, while HVDC 2 is out of service for maintenance purposes etc.

The new system configuration requires in-depth knowledge of all relevant technical aspects, including e.g. the involved control systems performance and robustness for all possible operating conditions. The transmission system operator might impose new control requirements when HVDC is going to be used for OWPP grid connection and the dynamic compliance specifications might change. This sets up a need to develop new strategies for ensuring robustness and adaptability, considering aspects such as fault-handling, ancillary services, congestion management, etc. It is therefore important to analyse and assess all possible control aspects related to the interaction between the OWPP and the HVDC system.

The paper will present a review of the state-of-the-art of grid integration of large OWPPs using HVDC for grid connection, on the involved PEDs in the OWPP and in the HVDC system. Furthermore, on the PEDs control capabilities and on how the testing of the control systems is currently being carried out. Based on the review, the paper will give a detailed description on the challenges that need to be addressed in order to ensure robust operation of the OWPP.

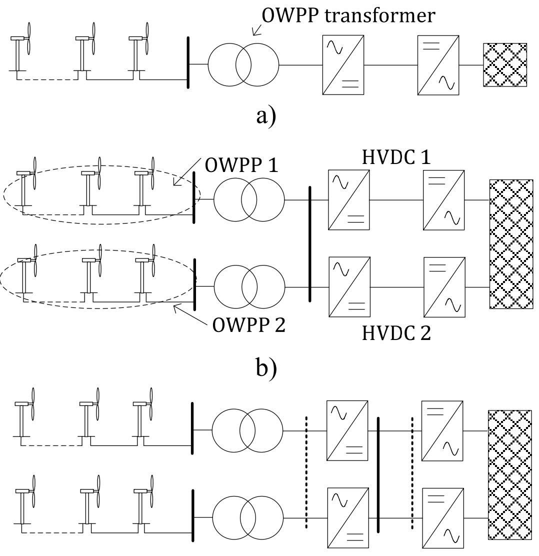


Figure 1 **Simplified single line diagrams of grid connection of OWPP(s) using a) point-to-point (P2P) VSC-HVDC b) parallel P2P connected on the offshore AC side, fed by multiple OWPPSs c) multi-terminal. HVDC converter transformers (if any) have not been included in the figures.**

The paper will present how DEWP, market leader in development and operating of OWPPs, is addressing these challenges through three coordinated PhD projects in close collaboration with leading academia within the field. The paper is organised following the separation between the three PhD projects:

Section II presents the project "*Harmonics in Large Offshore Wind Farms, Employing Power Electronics in the Transmission System*", dealing with the harmonics in the OWPP and on how the controllers employed in the respective PEDs interact with each other from a stability perspective in the frequency range above 50 Hz.

In Section III, a description of the project "*Communication and Control in Clusters of Wind Power Plants Connected to HVDC Offshore Grids*" is given. The project focuses on the investigation of problems concerning the efficient coordination of HVDC system and OWPPs controllers to properly perform dedicated control features such as the provision of system services (both to the AC and the DC grid), fault-handling, coordination of multiple OWPPs behind HVDC converter(s), etc.

Finally, Section IV draws the attention to the project "*Offshore Wind Park Control Assessment Methodologies*", that investigates the control system architecture top-down of an OWPP and how the complex dynamics can be reduced and compiled into a set of generalised parameter specifications for components in an early stage of planning to minimise design based problems at a later stage.

II. Harmonics in Large Offshore Wind Farms, Employing Power Electronics in the Transmission System

Stability assessment and control design in conventional power systems have been carried out on basis of the assumption of sinusoidal excitation at fundamental power system frequency [5]. Although harmonics exist due to non-linear components such as e.g. the line commutated converter (LCC) HVDC, they have been assumed to be negligible with regard to power system stability. However, due to the increasing application of PEDs in e.g. OWPPs this assumption is no longer valid, as harmonics may lead to unpredicted and unwanted interaction between components, which eventually may lead to instability [6].

State-of-the-art full-scale back-to-back power converters are typically used in the WTGs, which are grid-friendly in many aspects, including their relatively low harmonic emission level [7]. However, OWPPs have a significant medium voltage cable network, and depending on the grid connection solution, long HVAC cabling. The distributed cable capacitances are prone to cause resonances within the bandwidth of the closed loop control systems of the PEDs in the WTGs and therefore affect the stability of the closed loop control system. Operating experiences in conventional HVAC grid connected OWPPs have shown that these converters can interact with each other, with the internal OWPP electric system as well as the external network causing so-called harmonic instability problems. Harmonic instabilities involve the interaction between the AC system, the WTG converter itself and its control system and have the adverse effect in OWPPs of voltage oscillations prior to disconnection of the OWPP, leading to lost revenue unless countermeasures are taken.

The observation of harmonic instabilities can be traced back to mid-sixties [8-9] for LCC-HVDC schemes. One of the most significant incidents with the application of modern PED was reported in the mid-nineties, where the Swiss railways experienced malfunction of the electric rail vehicles, leading to shutdown of the traction system. The malfunction was explained to be caused by resonance in the Swiss 132 kV network, which was excited by the control systems used in the PEDs of the electric rail vehicles [5].

For high power VSC-HVDC transmission system applications, the three main topologies utilised so far are the two-level, three-level and the modular multilevel cascaded converters (MMCC) [1,10-12]. Whereas only the Trans Bay Cable project utilises the merging MMCC technique [1,3], the two- and three-level topologies have found their application in a number of installations, as outlined in Table I [1].

TABLE I Overview of Selected VSC-HVDC Projects

Installation	Installed	Manu-facturer	P_{rated} [MW]	Converter topology
Gotland	1999	ABB	50	2-level
Murraylink	2002	ABB	220	3-level
Estlink	2006	ABB	350	2-level
BorWin1 (OWPP)	2009	ABB	400	2-level
Trans Bay Cable Project	2010	Siemens	400	MMCC
BorWin2 (OWPP)	2013	Siemens	800	MMCC
HelWin1 (OWPP)	2013	Siemens	576	MMCC
DolWin1 (OWPP)	2013	ABB	800	MMCC
SylWin1 (OWPP)	2014	Siemens	864	MMCC
South-West Link	2014	Alstom	1440	MMCC
HelWin2 (OWPP)	2015	Siemens	800	MMCC
Dolwin2 (OWPP)	2015	ABB	900	MMCC

Table I indicates that the trend in future VSC-HVDC installations is to employ the MMCC for power transmission and grid connection of OWPPs. The MMCC VSC-HVDC, introduced in [13], synthesises a high quality sinusoidal voltage waveform by incrementally switching a high number of voltage levels, thus having low harmonic emission and low filter requirements.

A. Purpose of PhD project

Although the MMCC based VSC-HVDC provides close to sinusoidal fundamental voltage and current waveforms into the system, it is still of high importance to the wind power industry to investigate and acquire detailed knowledge on the possible interaction (from a harmonic perspective) between the control systems used in the PEDs in the WTGs and in the offshore VSC-HVDC terminal in order to design a robust system.

This industrial PhD project will mainly focus on investigating the best possible way(s) to perform harmonic studies in VSC-HVDC grid connected OWPPs. The project is aimed at gaining new methods and models, which will contribute to achieve a high degree of reliability of future OWPPs mainly based on the VSC-HVDC grid connection. The project will investigate the possibility of developing detailed models, which are independent of manufacturer provided data, as this is normally confidential.

By achieving a better understanding of the complexity of how such PED systems interact with each other, seen from a harmonic perspective, it will be possible to optimise design of harmonic filters, reactive compensation etc. Furthermore, the increased know-how will also enable DEWP to give relevant input during the compliance assessment of an OWPP. The PhD project will also enable DEWP to ask for the right information for the VSC-HVDC system in due time during the design of an OWPP and will lead to improvement in the reliability of future OWPPs.

B. Project objectives

The following list summarises the main expected deliverables from the PhD project:

- Obtain detailed knowledge of MMCC technologies for wind power integration (VSC-HVDC and static synchronous compensator (STATCOM)).
- Develop and validate appropriate models of the MMCCs. In time, frequency and harmonic (modulator) domain, where found applicable.
- Conduct field measurement campaign for model validation.
- Investigate wind farm stability issues for frequencies above the fundamental frequency with widespread use of PEDs.
- Compare different stability assessment methods in time and frequency domain.
- Develop a best-practice for harmonic stability assessment in offshore wind farms.
- Investigate involved parameters influence on the stability margins.
    - Sensitivity analysis of e.g. HVDC control parameters, grid strength etc.

III. Communication and Control in Clusters of Wind Power Plants Connected to HVDC Offshore Grids

Along with technical issues related to harmonics, the wide-spread utilization of PEDs poses, on the one hand, new challenges related to more classical control facets, such as normal operation or delivery of system services, while offering, on the other hand, more opportunities for tackling them. This is obviously true also for VSC-HVDC [14].

When the picture involves OWPPs (e.g. future HVDC projects indicated with OWPP in Table I), additional coordination may be necessary to guarantee the optimal operation of the OWPP and the HVDC transmission system. New dynamic requirements are brought about by the introduction of the VSC-HVDC connection, the behaviour of which is substantially different from that of a classical power system. One direction of research is related to the excitation of the offshore AC islands (left parts of **Error! Reference source not found.Error! Reference source not found.**Figure 1), where, at least initially, single HVDC converters will have to shoulder the main control burden to guarantee evacuation of the power, by fixing the voltage magnitude and angle (so called *U/f* control), and the OWPP will synchronise in the usual way [15-16]. However, more advanced and generalised approaches have also been proposed, and are expected to offer a more robust and flexible solution when the number of HVDC converters feeding the same island will increase [17-19].

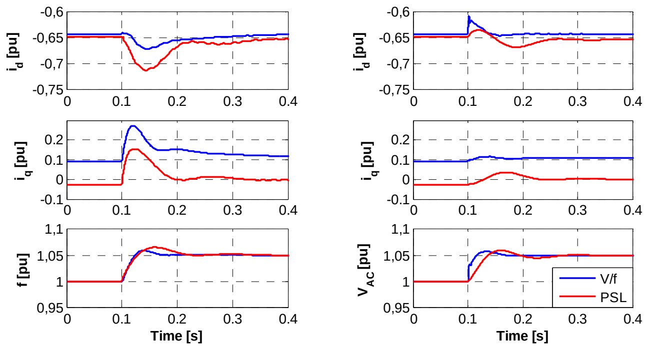
The other focus area is the coordination of HVDC converter and OWPP controllers during normal operation [15-16], delivery of ancillary services [15,20-22] and faults of various nature [15-16]. Further research is directed to address the same challenges, but is considering more complex multi-terminal DC networks, e.g. [23-24]. However, further room for research is left, in particular directed towards:

- A more detailed investigation of the aspects touched upon by the cited references, with careful assessment of dynamic requirements and control and coordination issues when considering real OWPPs and their relatively slow controllers.
- Handling of events that so far, to the authors' knowledge, have not been touched upon, such as for instance the response to HVDC converter tripping or a thorough theoretical analysis of short circuit in offshore AC islands.

The control challenges to be solved come along with the utilisation of an appropriate level of communication. Studies have been initiated, for example, on simple networks [21-22] and with focus on frequency control, where communication seems to offer satisfying performance. However, more complex grid layouts might suffer robustness lack when relying heavily on real-time fast communication and solutions have been proposed, e.g. in [25-26].

A. Purpose of PhD project

In order to facilitate the deployment of very remote OWPPs through VSC-HVDC transmission, it is important to provide a contribution to fill the research gaps outlined above. Issues concerning the excitation of offshore islands should be looked at, by comparing techniques proposed to date or suggesting new improvements. As an example, a simple comparison between a simple master-slave approach (*U/f* control [15]) and the power synchronization loop (PSL) [18] is depicted in Figure 2, where voltage and frequency steps have been tested at the offshore station of a P2P HVDC connection for OWPP. It can be seen that the schemes offer similar performance. Future work will more thoroughly assess the similarities and differences. The steady-state differences in direct and quadrature current are due to the different reference for the angle, which is the grid side of the converter transformer for the *U/f* and the converter internal voltage for the PSL.



(a) (b)

Figure 2. Offshore converter control: comparison between current vector control (*U/f*) based scheme and power synchronisation loop (PSL) based scheme. (a) frequency reference step, (b) AC voltage reference step.

On the other hand, control coordination between VSC-HVDC networks and OWPPs should be further investigated, with special attention drawn upon the actual need for fast communication. In [22], a frequency control scheme based on communication proved to perform equivalently to a coordinated control involving offshore frequency and DC voltage. Further work is needed in the area, expanding it to other services such as power oscillation damping and HVDC voltage control.

B. *Project objectives*

The main objectives of the study are the following:

- Developing and comparing solutions for the connection of OWPPs through HVDC network with respect to normal operation (delivery of scheduled energy).
- Investigation of alternatives for provision of currently required system services.
- Investigation of new possible services and requirements and characterisation in terms of their direct influence on the OWPP's operation and control and analyse solutions thereto.
- Investigate other control problems such as fault-handling (e.g. short circuit and load rejection), robustness against communication faults.
- Assessment of communication needs for all the above items.

IV. Offshore Wind Park Control Assessment Methodologies

Every aspect of control design is a trade-off between performance and stability, and the OWPP developer relies on its suppliers to deliver systems that conform with the performance specifications as set by the national grid code. Although the suppliers deliver the subsystems, the OWPP developer is liable for any delay or unforeseen situations, even if the situation is caused by a malfunction in the delivered subsystem. One of the challenges in minimizing the risk of malfunction is to validate the implementation of the control systems without having direct access to the mathematical models used. In order to conform with the Intellectual Property Right (IPR) of the industry, generic models of the most used WTG structures have been developed to provide a baseline for stability and transient analysis by IEEE, IEC and CIGRE [28-30]. Various PhDs have also investigated the representation of type 1-4 WTG's, notably [27]. The use of generic models is shown to represent the dynamics of a WTG during steady state operation and fault precisely [31].

A challenge in WTG modelling is adequate level of detail in the component descriptions to represent the interactions and dynamics of interest. One focus area of the project is the dynamic interaction between controllers associated with the individual type 4 permanent magnet synchronous generator (PMSG) WTGs in a small scale OWPP and the risk of having oscillations and unforeseen dynamics which eventually can lead to instability. The generic models developed include unsolicited simplifications with respect to generators and critical components such as the PEDs to minimise simulation requirements, and are often represented in the frequency domain and not in a form suitable for control system analysis. Work has been done on restructuring and expressing both the physical and the control systems in a non-linear state-space model [33], but further research is needed to include dynamics of interest.

Another focus area is the analysis of the park level control systems such as the static compensator (STATCOM) and power distribution. The second-to-minute timescale of the problem dictates detailed WTG modelling, which must represent the used WTG in the OWPP. A power control system identification approach is suggested by [34] and was followed up by a simplified overall park control design [35].

As mentioned in the previous sections, experiences from existing OWPPs have led to a renewed interest in investigating the maturity and interaction between control systems both in the WTGs but also on a park level. Currently, the specifications set for the operation of an OWPP vary nationally even though work has been done on harmonizing grid code requirements [32].

Commissioning tests are performed to just ensure compliance with grid code in order to achieve operation notice, but it does not convey a precise picture of the limitations of the OWPP. To the author's best knowledge, no research has been conducted with regards to worst-case excitation and testing methodologies.

The research done on modelling of OWPPs and WTGs is primarily focused on standardization due to industry IPR, but every research objective requires another level of detail and a well-defined structure for the study of WTG control system interaction and its key parameters is needed to lower the risk of investing in OWPPs.

A. Purpose of PhD project

The main challenge approached in this project is modifying and combining generic models as to generate a structure suitable for estimating key parameters in both WTG and OWPP control system interaction using in-house knowledge concerning the underlying dynamic systems. This effort can be split into two sub-objectives:

1. Interaction between the control systems operating on the WTGs and complications in a small scale 2-WTG system.

2. Stability and performance of the OWPP with regard to high-level control system loops such as the STATCOM local voltage, reactive power control and distribution of set points from the park pilot.

The model distinction required for the analysis of (1) and (2) is significant and the frequency range of interest is diverse. In (2), the model is proposed to be a power source parameterised as a modified Hammerstein model due to the nonlinearity, i.e. a static nonlinearity combined with linear dynamics, which can represent the steady state and transient properties [34]. This split structure is repeated in the WTG modelling of (2), which will be described as a nonlinear state-space model using state-space averaging techniques to represent the switching systems. The purpose is not to design new control systems, but apply robust control theory on the generated structure in order to assess challenging operation areas of the system, i.e. operation and stability bounds given a conservative control structure, and design methods to excite and test real-life OWPPs in order to minimise risk.

Another aspect of the project is the study of physical points of measurement used in the feedback control laws in the WTG and on a park controller level in order to optimise SCADA design which is the backbone of the OWPP [36].

The objective of the project as a whole is to put emphasis on the critical aspect of ensuring compatibility, robustness and having control system specifications to complement the load-flow and dynamic simulations conducted by the OWPP developer.

B. Project objectives

The objectives are summarised as follows:

- Design an appropriately structured WTG and system model top-down to investigate OWPP excitation and feedback loops using data from field measurements in one of DEWP's parks.

- Design adequately detailed model for small scale system control interaction based on a conservative control scheme.

- Investigation of key sensitivity parameters in both high-level and low-level models using non-linear robust analysis.

- Determine worst-case excitation as an amendment to the commissioning testing to minimise risk and guarantee operation.

- Generate a minimum requirement for WTG and OWPP control systems in order to ensure robustness with on-par performance.

V. Summary

The purpose of the paper has been to review the state-of-the-art of grid integration of large OWPPs using HVDC for grid connection. Furthermore, the paper has outlined some of the selected challenges, which are being addressed in three related PhD projects in close collaboration between DEWP and leading academia within the field. The state-of-the-art within the different research areas has been pictured in the paper and an outlook for future research has been proposed.

The three projects described in the paper are aimed at gaining an overall understanding of OWPP operation in connection with HVDC networks, focussing on modelling, communication and control and spanning over a wide dynamic range, going from power system frequency control (several seconds range) to harmonic stability (few milliseconds range).

The main challenges to be addressed have been pointed out:

- Assessment of harmonics and harmonic stability in OWPPs with substantial amount of PED (Section II).

- Control coordination and communication in HVDC connected OWPPs (Section III).

- Provision of simple but reliable models for more thorough assessment of control performance of OWPPs (Section IV).

Harmoniously coordinating the research in the three areas will help the OWPP developer to obtain an as holistic as possible picture of challenges related to OWPPs with HVDC connection. The projects aim at providing tools for addressing these possible challenges in due time in the design phase of a future OWPP.

VI. Acknowledgment

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